

Distance and backhaul in commodity transport modeling

Joyce Smith Cooper · Liila Woods · Seung Jin Lee

Received: 17 February 2007 / Accepted: 2 November 2007 / Published online: 9 May 2008
© Springer-Verlag 2008

Abstract

Background, aims and scope The goal of this work is to provide methodological information for modeling distance and backhaul for commodity transport in a life cycle inventory (LCI). The scope includes a review of modeling parameters accounted for in transport unit process models and accounted for in unit process models using transported materials. Assumptions related to backhaul (or return trip) and transport distance are characterized and evaluated. A case study explores the contribution of transport and the bearing of assumptions on the life cycle of select US-produced metals.

Methods Backhaul and distance estimation assumptions and methods are described and applied. Commodity transport energy consumption and emissions (including life cycle fuel production) are estimated as a function of assumptions for distances traveled (based on data from a commodities transportation survey) and backhaul (based on a review of related literature) for transport unit processes and example US metal LCIs. The results estimate the contribution of transportation to life cycle total, fossil, and petroleum energy consumption and eight air emissions: CH₄, CO, CO₂, N₂O, NO_x, PM, SO_x, and NMVOC for aluminum, brass, copper, iron, and carbon, and stainless steels.

Results When evaluating transportation processes unincorporated into the metals LCIs, we find a 21–62% and a 61–91% increase in life cycle flows for the inclusion of distance data confidence intervals and the inclusion of backhaul, respectively. We presume that these results also apply to transport-dominated LCIs, such as those evaluating alternative uses for wastes. Next, when commodity transport is incorporated into the metal LCIs, we find the contribution to the metals life cycle to exceed 10% of the life cycle values of NMVOC emissions (aluminum, iron, and carbon steels), CO emissions (secondary aluminum), NO_x emissions (aluminum, secondary copper, iron, and steels), N₂O emissions (aluminum, brass, secondary copper, iron, and carbon steels), and SO_x, CH₄, CO₂, and greenhouse gas emissions (basic oxygen furnaces (BOF) carbon steel) and to exceed 25% for NMVOC emissions (BOF steel), NO_x emissions (secondary aluminum, iron, and carbon steels), and N₂O emissions (BOF steel). Also, when commodity transport is incorporated into the metal LCIs, we find little variation in the results related distance confidence intervals and the inclusion of backhaul, seeing on average a 2% change in the contribution of commodity transport to the metal LCIs for variation in assumptions. Finally, our normalization revealed a very small, consistent commodity transport contribution of NO_x for all metals and a small contribution to all emissions by carbon steel on a national scale. Thus, we find the importance of distance and backhaul assumptions on a sliding scale: we find travel distances, distance confidence intervals, and the inclusion of backhaul to be important to transportation processes and presumably, transport-dominated LCIs; we find travel distances to be important when commodity transport is incorporated into metal LCIs; and we find commodity transport not important to our normalized results for the metals studied.

Responsible editor: Robert Anex

J. S. Cooper (✉) · S. J. Lee
Department of Mechanical Engineering,
University of Washington,
Box 352600, Seattle, WA 98195-2600, USA
e-mail: cooperjs@u.washington.edu

L. Woods
Five Winds International,
Boston, MA, USA

Discussion We presume all LCIs will fall somewhere on this sliding scale, and that the estimation methods presented here will be useful in future studies. To support transparency of results, LCI construction should clearly state transport assumptions and provide well-developed meta data noting regional vehicle/vessel energy and emission intensities; load factor; vehicle/vessel manufacturing, maintenance, and disposal; and infrastructure construction, operation/maintenance, and disposal for transport unit processes as well as load and distance for unit process models using transported materials. Finally, the diminishing returns of transportation data collection should be evaluated on the basis of whether the commodity transport distance can actually be changed.

Conclusions Commodity transport can be important to unnormalized LCI results and can be sufficiently captured by representative (as opposed to a range of) distance assumptions for the metals studied. Because commodity transportation was found to be important in our un-normalized results, we note that, depending upon the goal of the study, intentional omission of commodity transport in metal LCIs, and until shown otherwise, other LCIs, without further investigation, may not be defensible.

Recommendations and perspectives More attention is being paid to the contribution of transportation within system life cycles, particularly for food and bioproducts systems. Here, we note that well-documented assessments culminating in transparent results can be used to identify local sourcing or facility location priorities for metals and thus for materials beyond notorious transportation-oriented systems. Further, whereas it may be possible to develop reliable regional and commodity-specific rules-of-thumb for backhaul and distance/co-location that can be automated within the construction of a LCI, comprehensive commodity transport modeling remains dependent upon data for regional production mixes and the estimation of representative transport distances. Recommendations for future research include assessments beyond metals; assessment of a broader range of emissions, land use, and noise; and the inclusion of transportation from and to overseas destinations.

Keywords Backhaul · Co-location · Commodities · Distance estimation · Metals · Return trip · Transportation

1 Introduction

Like electricity generation, commodity transport is a part of most, if not all, life cycle assessments (LCAs). Select LCA practitioners present the contribution of transportation as part of the inventory and impact assessment results, at times showing transportation to be an important contributor to the system flows or impact (He and Wang 2000; International

Iron and Steel Institute 2004a, b; AusLCANet 1998; Jørgensen et al. 1996; Frees and Weidema 1998; Ekvall et al. 1998; Eriksson et al. 2005; Ramjeawon 2004; Jungmeier et al. 2002; Silvenius and Grönroos 2003). In these studies, the contribution of transportation is found to vary widely by product and flow type, even within a single study where variations in study-specific methodologies, data, and assumptions should not be a factor. Despite these findings, many LCAs in archival and grey literature intentionally exclude transportation considerations and/or do not provide adequate descriptions of the assumptions used in the preparation of transportation data or in the use of these data to construct a life cycle inventory (LCI; Woods 2006).

General methodological guidance for transport modeling is presented by the SETAC (Society of Environmental Toxicology and Chemistry) LCA Working Group on Data Availability and Data Quality subgroup (Braam et al. 2001) and by Spielmann and Scholz (2005). The SETAC working group suggests that the most important cause of variation in energy consumption per distance traveled is the choice of mode with each mode represented by the same three classes of data: (1) fuel production: extraction, transport, refining, storage, and transport; (2) transportation: engine type, fuel type, and exhaust gas cleaning; and (3) transport performance: vehicle type and size, load, backhaul (a.k.a. return trip), and traffic conditions. Further, the SETAC Workgroup suggests that combustion during transport is much more important than energy consumption and emissions during oil extraction and fuel production and that the most important parameters for combustion during transport are fuel consumption and the loading factor. From this point, additional detail on the development of freight transport unit process models is provided by Spielmann and Scholz (2005). These authors highlight variations in results between modes and including variations in truck size, variations in regional motorway conditions, and consideration of backhaul. They also highlight the importance of including not only vehicle operation but also vehicle manufacturing, maintenance, and disposal as well as infrastructure (roads, tunnels, bridges, etc.) construction, operation/maintenance, and disposal.

The guidance provided by the SETAC working group and by Spielmann and Scholz is very helpful in the development of a LCI where the specific origin and destination of each material and fuel are known and instances in which empty vessel and vehicle return to the origin can be identified (see for example the LCI presented by Frees and Weidema 1998). However, for life cycles using, and thus transporting, commodities with multiple national or international production sites and subject to a variety of backhaul practices, little guidance is provided for setting assumptions. Thus, here we summarize related

modeling methods and assumptions and investigate the influence of related assumptions on LCI and LCA results.

2 Distance and backhaul modeling methods and assumptions

2.1 Estimating the distance from origin to destination

For unit processes using commodity materials, the scope of the distance estimation between unit processes can become complex when multiple national production sites and imports are considered. In such cases, the practitioner might represent the unit process using the commodity as one that demands (1) a percentage of production from each importing unit process, each including barge, rail, and highway transport from the point of production to ports of export, (2) ocean transport of the commodity to receiving port, and (3) ocean, barge, rail, and highway transport from the receiving port to the point-of-use, and (4) ocean, barge, rail, and highway transport from the national production sites to the point-of-use. As such, transport distances may be estimated on a point-to-point basis, using for example a GIS-based logistics software (e.g., Caliper's TransCAD described at www.caliper.com/tcovu.htm), using web-based distance estimation programs (e.g., local.live.com/ and distances.com/), or using an appropriate series of great circle distances. As an example of the latter, we have used a three-point great circle distance to estimate ocean transport distances (item 2) such that the first point represents the longitude and latitude of the port at the country of origin, the second point represents longitude and latitude of an extremity of a continent that the vessel must circumvent to get to the third point, which is represented by the longitude and latitude at the port receiving the goods. Use of this method requires identification of commodity origins and destinations and import percentages. In the US, these data can be found through the Geological Survey Commodity Statistics and Information and from the US Department of Transportation's Freight Analysis Framework (FAF).

Also in the US, a portion of the transport distance estimation data (specifically, item 4 in the paragraph above for ocean, barge, rail, and highway transport from the national production sites to the point-of-use) are collected through a national survey known as the US Commodity Flow Survey (CFS; Bureau of Transportation and Statistics 2004).¹ A method for the use of CFS data in LCA is in part described by He and Wang (2000) to estimate a range of

US commodity transport distances.² Specifically, for each transport mode (truck; rail; water as shallow draft, great lakes, and deep draft; air; and pipeline) the CFS presents both single and multi-mode transport for commodity groups by Standard Classification of Transported Goods (SCTG) codes. Because transport unit processes are based on single modes and because CFS does not include data that would assist in dividing multi-mode into single-mode legs, if we assume that single-mode distances are representative of US transport for each commodity. For the single-mode distances, CFS data are provided for 'average single-mode miles per shipment', 'total single-mode ton-miles' (summing water, rail, truck, air and pipeline transport), and the 'single-mode ton-miles' for each mode. Because not all shipments use all modes, the 'share' of each mode is defined as:

$$s_{i,c} = \frac{B_{i,c}}{B_{T,c}} \quad (1)$$

where:

- $s_{i,c}$ share of mode i for commodity c
- $B_{i,c}$ single-mode ton-miles for mode i for commodity c
- $B_{T,c}$ total single-mode ton-miles for commodity c

The share-weighted average transportation distance for each transportation mode is calculated using the 'average single-mode miles per shipment' and the share for each transportation mode:

$$D_{i,c} = d_{i,c} s_{i,c} \quad (2)$$

where:

- $D_{i,c}$ average share-weighted distance for transportation mode i for commodity group c (miles)
- $d_{i,c}$ average single-mode miles per shipment for transportation mode i for commodity group c (miles)

Finally, the coefficients of variance for all CFS parameters ($B_{i,c}$, $B_{T,c}$, and $d_{i,c}$) can be used to estimate the 90% confidence intervals for each mode and commodity group.

Next, we recognize that although the use of conveyors, loaders, and other on-site materials movers may apply, commodity transport between unit processes should be assumed to be zero if the processes are located at the same facility (the processes are co-located). The need to understand co-location on a process-by-process basis comes from the fact that current LCI data available to practitioners comes from a variety of sources (e.g., measured or primary data or engineering models of industrial practices) with unit process boundaries (what activities are modeled together) chosen on the basis of the available data as opposed to strict

¹ Despite the statement in the CFS documentation "imported products are included in the CFS at the point that they left the importer's domestic location for shipment to another location" critiques of the use of CFS data note this is not the case (e.g., Fowler 2001).

² Because the details concerning the exact use of the CFS data were not included in their report, the method described here adds detail to the structure described by He and Wang (2000).

consideration of co-location. Thus, some unit process data will include all activities that occur at a single site and other data will separate process steps at a single facility.

Again, whereas co-location will be apparent in a LCI based on very specific hauling conditions, this will not be the case in models of commodity transport. Because we did not find guidance in archival or grey LCA literature dealing with co-location, in the absence of very specific hauling data and to facilitate commodity transport modeling, we define the following ‘co-location rules’ by noting that transport between unit processes should be included unless any of the following apply (modified from Woods 2006):

- Flows designated as “in ground” that are converted into a flow designated as ‘at mine’ can be assumed not to be transported between unit processes.
- Flows of water, treated water, and air can be assumed not to be transported between unit processes.
- Material processing steps such as crushing, milling, packing, or a phase change can be assumed to be co-located with the preceding unit process.
- Special co-location situations identified in literature.

Application of these rules requires that the location of inventory flows be specified, preferably in the name of the flow, as is the general rule in for example the EcoInvent database (Swiss Centre for Life Cycle Inventories 2006). Each of the four rules requires further investigation for each unit process through literature review. For example, insights into the co-location in the US can be found in United States Geological Survey (USGS) information sources. Further, although the second rule may work well in the US and other regions with well-developed municipal water systems, it may not apply in regions that conventionally transport water for industrial purposes.

2.2 Accounting for backhaul

Once the distance from origin to destination is estimated (e.g., either zero for co-located unit processes or the share-weighted average transportation distance for each commodity), backhaul, or return trip, is presumably attributed to the unit process at hand if the vessel or vehicle is not subsequently moving goods for another product system. Again, for commodities in the absence of very specific hauling conditions, little consistency was found in backhaul assumptions used in LCA studies or studies investigating specific transportation systems:

- Water transport studies either (a) did not mention backhaul, (b) stated backhaul was intentionally not included, (c) assume a backhaul factor of 34–35% of the energy use and emissions of fronthaul (for barge transport), or (d) incorporate a load factor of 60% for the return trip, equating to a backhaul factor of 76% (again for barge transport), or (e) incorporate a load

factor of 70% for the return trip, equating to a backhaul factor of 89% (for ocean tanker transport of liquid fuels; Frees and Weidema 1998; Ekvall et al. 1998; Silvenius and Grönroos 2003; Swiss Centre for Life Cycle Inventories 2006; Wang 2005; Baumel et al. 1985).

- Rail transport studies either (a) did not mention backhaul, (b) stated backhaul was intentionally not included, (c) assume a backhaul factor of 30% of the energy use of fronthaul, or (d) provide a model for empty train energy use and emissions (Frees and Weidema 1998; Ekvall et al. 1998; Swiss Centre for Life Cycle Inventories 2006; Wang 2005; Baumel et al. 1985; Office of Transportation and Air Quality 2000).
- Truck transport studies either (a) stated backhaul was intentionally not included, (b) assume a backhaul factor of 30–68% of the energy use and emissions of fronthaul, (c) provide models for partially loaded or empty vehicles, or (d) assume backhaul is equivalent to fronthaul (for liquid fuel transport; Silvenius and Grönroos 2003; Swiss Centre for Life Cycle Inventories 2006; Wang 2005; Baumel et al. 1985; Office of Transportation and Air Quality 2000; Federal Highway Administration 2002; American Council for an Energy-Efficient Economy 1997; Vachal and Reichert 2000; Upper Great Plains Transportation Institute).

Thus, when specific commodity hauling conditions are not known, backhaul factors of 0 to 89% for water transport, 0 to 30% for rail transport, 0 to 100% for truck transport might be appropriate for use in LCI.

2.3 Evaluation of assumptions

As described above, although a part of most system life cycles, little methodological information was found related to distance estimation and backhaul assumptions in a LCI. It would seem that there is some point at which consideration of variations in distance and backhaul are only a small percentage of a commodity’s total energy use, emissions, and impact and that managing related assumptions would not be important to LCI or LCA results. As follows, we investigate the contribution of the life cycle of fuel production and vehicle/vessel operation for US commodities as a part of select metals life cycles, as a first step in determining the point at which diminishing returns occur.

3 Metal case studies

3.1 Goal and scope

For our case studies, our goal was to evaluate the implications of backhaul and transport distance assumptions

on LCA results for an example set of metals with the transportation contribution represented by the fuel production life cycle and vehicle/vessel operating emissions. Our study region was the US and the scope of our case studies from raw materials acquisition through the point-of-use for electricity, fuels, and refinery products (based on data from the GREET model (Wang 2005) and raw materials acquisition through the point-of-use for metals production (based on data from EcoInvent³, Swiss Centre for Life Cycle Inventories 2006). The analysis included 99.9 mass% of unit process inputs, with the exception of the production of explosives,⁴ infrastructure construction/operation/maintenance, and waste management process construction/operation/maintenance (noting that transport to waste management was included). The LCI tracked life cycle total, fossil, and petroleum energy consumption and eight air emissions. All remaining ISO 14040 series information for this study (for goal and scope definition, inventory analysis, impact assessment, data quality analysis, and interpretation) is presented by Woods (2006) for steel, with commensurate construction used for the additional metals described here.

In the development of our LCI, we first applied the co-location rules presented in Section 2.1. Example unit process information is provided for our analysis of steel in Table 1 for the use of basic oxygen furnaces (BOF) and electric arc furnaces (EAF) in steel production. Transportation of commodities not covered under the co-location rules were calculated based on the mass consumed (with transportation assigned to the receiving unit process).

For distance, we estimated the variation in the share-weighted transport distance for 21 groups of commodities in the US used in the metal case studies. We tested backhaul factors⁵ of 0 for transport by ocean freighter, 0 to 76% for barge transport, 0 to 30% for rail transport, 0 to 68% for truck transport other than liquid fuel transport, and assumed backhaul was equivalent to fronthaul for liquid fuel transport are assumed to capture the range of values noted above. We chose these data based on the wide range of values identified in our review of literature and in the absence of a method that links backhaul practices to specific commodity types (with the exception of liquid fuel transport for which we are assuming vehicles must be

dedicated to fuels) and to determine if these variations made a difference in the LCI and LCA results.

For fronthauls and non-zero backhauls, we used a 90% confidence interval of transport distances for front and backhauls using the CFS. The CFS presents data by SCTG code for increasing levels of aggregation from one-digit to three-digit codes. For example, SCTG32 is a two-digit code representing “base metal in primary or semifinished forms and in finished basic shapes” which subsequently includes the three-digit codes for iron and steel in primary forms, in semifinished forms (SCTG321); flat-rolled products of iron or steel (SCTG322); bars, rods, angles, shapes, sections, and wire, of iron or steel (SCTG323); and nonferrous metal, except precious, in unwrought forms, in finished basic (SCTG324). Given this structure, if a single data point (e.g., miles-per-shipment or ton-miles) does not meet publication standards because of high sampling variability or poor response quality, the data for three-digit or even two-digit codes are omitted from the CFS. As a result, data from the CFS three-digit SCTG code were used in our LCI whenever possible in distance calculations. If three-digit code data were omitted from the CFS, then data from the two-digit SCTG code were used. In the rare case when the two-digit value was not available, data from the one-digit SCTG code were used.

Finally, the energy and transport unit process models for our LCI are presented in Tables 2 and 3 and were based on data extracted from the GREET model (Wang 2005) with the exception of ocean freighter transport which was adapted from the USEPA’s analysis of commercial marine vessels (Office of Transportation and Air Quality (2000). Truck transport for all commodities was assumed to be by Class 8B Diesel Truck with the exception of the transport of chemicals. For chemical transport, it has been assumed that 62.5% move using Class 8B Diesel Trucks and 37.5% move using Class 6B Diesel Trucks (as in He and Wang 2000). Also, whereas the electricity production mix for the US was assumed to be 2.9% residual oil, 16.3% natural gas, 51.5% coal, 20% nuclear, 1.2% biomass, and 8.1% from other sources, the electricity production mix for the production of bunker fuel was assumed to be 6.9% residual oil, 19.3% natural gas, 39.9% coal, 15.7% nuclear, 0.83% biomass, and 17.4% from other sources based on the EIA energy statistics (International Energy Agency 2006) for the world average.

3.2 Inventory results

Table 4 presents commodity-specific transport results prior to their incorporation into the metal case studies. First, Table 4 lists the range of one-way share-weighted distances for the 21 commodity groups evaluated based on the CFS 90% confidence intervals. As shown, across the commodity

³ The use of EcoInvent process data to represent U.S. production processes other than electricity and fuels was highlighted as an issue in the data quality analysis. Where possible, data were compared and adjusted to U.S. data from AP-42 (Emissions Factors and Policy Applications Center 1986) and other sources as described by Woods (2006).

⁴ Although air emissions from blasting are included, explosive production processes have been left for future research.

⁵ For example, a backhaul factor of 76% means that the energy use and emissions for front and backhauls are estimated as 1.76 times the fronthaul energy use and emissions.

Table 1 Transportation assumptions for steel production unit processes

Process category	Unit processes (applicable system)	Materials included in commodity transport percentage estimation	Co-location rules applied
Materials acquisition	Mining and beneficiation processes for chromite, clays, coal, dolomite, ferronickel, iron ore, limestone, magnesite, and sodium chloride (BOF, EAF)	As applicable: bentonite, coal, explosives, hydrochloric acid, limestone, lubricating oils, quicklime, soda powder, sodium hydroxide, and sulfuric acid	Related minerals/ores in ground (rule 1)
	Bitumen, petroleum coke, hydrogen sulfide, and lubricating oils production (at refinery) (BOF, EAF)		Related feedstocks in ground (rule 1)
	Hard coal coke production (BOF, EAF)		Decarbonized water (rule 2) and coal (rule 1)
Chemical and allied products	Hydrated lime production and/or packing (BOF, EAF)		Quicklime (rule 4 Silvenius and Grönroos 2003)
	Hydrochloric acid production (BOF, EAF)	Sulfuric acid and sodium chloride	
	Limestone crushing, milling, washing, and/or packing (BOF, EAF)		Limestone (rule 3 Swiss Centre for Life Cycle Inventories 2006)
	Quicklime production (BOF, EAF)	Crushed and washed limestone	
	Soda powder production (BOF, EAF)	Limestone and sodium chloride	
	Sodium hydroxide production (includes diaphragm, membrane, and mercury cells) (BOF, EAF)	Sodium chloride, hydrochloric acid, and soda powder	
	Sulphuric acid production (BOF, EAF)	Secondary sulfur (from refinery hydrogen sulfide)	
Iron and steel related processes	Anode production (EAF)	Fireclay refractory, bitumen, petroleum coke, and cast iron	
	Cast iron production (EAF)	Basic refractory, quicklime, iron scrap, coal, and anode materials	Pig iron and oxygen (rule 4 United States Geological Society 2003)
	Iron pellet production (BOF, EAF)	Bentonite and coal	Iron ore (rule 4 Silvenius and Grönroos 2003)
	Iron sintering (BOF, EAF)	Hard coal coke, iron ore, and quicklime	
	Pig iron production (BOF, EAF)	Hard coal coke, coal, limestone, fireclay refractory, and iron ore and pellets	Sinter iron (rule 4 American Iron and Steel Institute 2006)
	Steel sheet rolling (BOF, EAF)	Lubricating oils, sodium hydroxide, sulfuric acid, and hydrated lime	Decarbonized water (rule 2); steel via BOF (rule 4)
	Steel via BOF (BOF)	Hard coal coke, dolomite, ferronickel, quicklime, beneficiated iron ore, and iron scrap	Pig iron and oxygen (rule 4 United States Geological Society 2003)
	Steel via EAF (EAF)	Basic refractory, coal, oxygen, quicklime, iron scrap, and anode materials	
	Basic refractory production (EAF)	Chromite, magnesium oxide, lubricating oils, and hydrated lime	
	Decarbonized water production (BOF, EAF)	Hydrochloric acid and hydrated lime	
Other	Fireclay refractory production (BOF, EAF)	Hydrated lime, lubricating oils, and clay	

groups, maximum one-way distances represent a 21–62% increase over the minimum one-way distance. Because energy use and emissions for transport are assumed to vary linearly with distance when only fronthaul is considered

(because the load is assumed to be the same for the entire trip), it follows that the maximum transportation-related life cycle total energy consumption and emissions also represent a 21–62% increase over the minimum. Next, the transport-

Table 2 Transportation mode operating fuel use and emissions (per ton–kilometer, at fronthaul load)

		US transport— ocean freighter, average payload 41,000 dry t	US transport— barge, average payload 1,360 t	US transport— freight train	US transport— medium-heavy truck, class 6 or 7 (7.3-t payload)	US transport— heavy-heavy truck, class 8a or 8b (18-t payload)
Residual oil (world source)	MJ	3.3E-01				
Residual oil (US source)	MJ		6.3E-01			
Diesel (US source)	MJ			5.7E-01	3.4E 00	2.0E 00
NMVOC	g	4.7E-03	2.3E-02	4.2E-02	1.3E-01	5.0E-02
CO	g	5.3E-02	6.1E-02	1.1E-01	3.7E-01	2.4E-01
NO _x	g	5.4E-01	6.2E-01	1.1E 00	1.8E 00	1.0E 00
PM10	g	1.3E-02	1.5E-02	2.8E-02	3.5E-02	1.7E-02
SO _x	g	4.7E-01	1.6E-01	5.0E-02	3.2E-02	1.9E-02
CH ₄	g	2.3E-04	1.1E-03	2.1E-03	6.2E-03	2.4E-03
N ₂ O	g	8.0E-01	1.2E-03	1.1E-03	9.3E-03	3.8E-03
CO ₂	g	3.6E 01	5.1E 01	4.2E 01	2.5E 02	1.5E 02

related life cycle total energy consumption is presented for each commodity, at the average distance of transport and varying the backhaul assumptions (both the inclusion of backhaul and the difference in the fronthaul and backhaul loads). Across the commodity groups, the maximum backhaul assumption represents a 61–91% increase over the no-backhaul assumption. Note that variation in co-location assumptions are not included in Table 4 but were instead incorporated into the LCI for relevant metals unit processes.

Table 5 presents the metals life cycle results, combining the commodity-specific distance and backhaul transport data and with co-location assumptions and unit process data for each LCA. Here, backhaul and distance assumptions have been varied for commodities other than those used in the production of electricity and fuels. The Table 5 results are presented for the 90% confidence interval of the share-weighted distances for each CSF SCTG category for truck,

rail, and water transportation linked with the minimum and maximum backhaul conditions described above. Note that the minimum of each range essentially represents the minimum share-weighted distance and zero backhaul.

As shown, commodity transportation was selectively found to be an important contributor to air emissions and that these values vary based on distance and backhaul assumptions. Of particular interest are instances in which (1) the maximum transport contribution exceeds 10% of the life cycle total for: NMVOC emissions (aluminum, iron, and carbon steels), CO emissions (secondary aluminum), NO_x emissions (aluminum, secondary copper, iron and steels), N₂O emissions (aluminum, brass, secondary copper, iron and carbon steels), and SO_x, CH₄, CO₂, and greenhouse gas emissions (BOF carbon steel); and (2) the maximum transport contribution exceeds 25% of the life cycle total for: NMVOC emissions (BOF steel), NO_x emissions (secondary aluminum, iron, and carbon steels), and N₂O emissions (BOF steel). However, the average difference between the minimum and maximum life cycle contribution of commodity transportation due to changes in backhaul and distance estimation assumptions was found to be only 2% and in only one case exceeded 10% (for N₂O emissions for BOF carbon steel). For our case study, since Table 5 reveals several instances in which the contribution of commodity transport exceeds 10, 25, and even 50% of the total life cycle flows and since the minimum of each range presented in Table 5 represents the minimum share-weighted distance and zero backhaul with little variation between the minimum and maximum results, we note that including representative travel distances is more important than the inclusion of backhaul and the inclusion of distance variation in the understanding of the role of commodity transport for the metals studied.

Table 3 Fuel life cycle energy use and emissions (per MJ)

		US residual oil, extraction to point-of-use	US diesel, extraction to point-of-use
Total energy	MJ	1.2E-01	1.5E-01
Fossil fuels	MJ	1.1E-01	1.5E-01
Petroleum	MJ	5.3E-02	7.1E-02
NMVOC	g	6.1E-03	7.3E-03
CO	g	1.2E-02	1.3E-02
NO _x	g	3.9E-02	3.9E-02
PM10	g	4.9E-03	6.2E-03
SO _x	g	2.1E-02	2.2E-02
CH ₄	g	9.3E-02	9.6E-02
N ₂ O	g	1.6E-04	2.0E-04
CO ₂	g	9.2E 00	1.2E 01

Table 4 Contribution of distance variation to the variation in life cycle total energy consumption

	One-way share-weighted distance transported (km, all modes)			Transportation-related life cycle total energy consumption: at the average distance and varying backhaul assumptions (MJ/t transported)		
	Min	Max	% Change	Min	Max	% Change
110: natural sands, except metal-bearing	90	144	60%	289	510	76%
133: dolomite	275	445	62%	596	1,057	77%
139: other nonmetallic minerals	433	560	29%	1,076	1,817	69%
141: iron ores and concentrates	314	473	50%	875	1,551	77%
149: other metallic ores and concentrates	363	502	38%	1,240	2,081	68%
151: non-agglomerated bituminous coal	336	460	37%	554	985	78%
159: other coal	114	183	60%	203	379	87%
191: lubricating oils and greases	244	358	46%	678	1,151	70%
199: other products of petroleum refining, and coal products	341	431	26%	580	1,066	84%
201: sodium hydroxide (caustic soda) and potassium hydroxide (caustic potash)	402	528	31%	737	1,410	91%
202: inorganic chemicals, not elsewhere classified	336	436	30%	761	1,335	75%
239: other chemical products and preparations	386	467	21%	1,823	2,956	62%
312: ceramic products	615	874	42%	3,294	5,319	61%
319: other nonmetallic mineral products	166	217	30%	505	840	67%
321: iron /steel in primary forms/in semifinished forms/or in powders	335	477	42%	1,615	2,625	62%
322: flat-rolled products of iron or steel	296	371	25%	946	1,568	66%
323: bars/rods/angles/shapes/sections/wire/of iron or steel	227	276	22%	732	1,216	66%
324: nonferrous metal/ex precious/in unwrought forms/in finished basic	324	398	23%	1,327	2,163	63%
331: pipes/tubes/fittings	236	327	39%	904	1,512	67%
411: metallic waste and scrap	159	243	53%	449	848	89%
412: nonmetallic waste and scrap, except from food processing	429	609	42%	1,190	1,999	68%

In order to investigate the importance of the inventory results, the contribution of transportation to materials production were compared to related US national statistics (Office of Air and Radiation 2006; Energy Information Administration 2006). The analysis found that the transportation contribution aside from that of carbon steel was only consistently above 0.02% of US emissions for NO_x, still ranging only from 0.02 to 0.5% of US NO_x emissions. Looking more closely at the carbon steel, in 2005 the US produced approximately 92.4 million M/T of steel, of which 44.9% was from blast oxygen furnace and 55.1% from electric arc furnace (United States Geological Society 2005). Assuming a net import reliance of 18% for iron and steel (United States Geological Society 2003) and that rolled steel is representative of US steel products in general, reveals NO_x, PM, SO_x, greenhouse gases, NMVOC, and CO emissions respectively at 0.48%, 0.13%, 0.06%, 0.05%, 0.03%, and 0.01% of the total US emissions. However, it is important to note that for the steel life cycle, PM emissions are not dominated by commodity transportation and represent 16% of the US total for all emission sources such that transport improvements might fall lower among priorities for improvement.

4 Discussion

Although we have modeled only a portion of the commodity transport life cycle (including only the fuel production life cycle and vehicle operation and only transport from production sites to the point-of-use), we find the importance of distance and backhaul assumptions on a *sliding scale*. First, we find a 21–62% and a 61–91% increase in life cycle flows for the inclusion of distance data confidence intervals and the inclusion of backhaul, respectively, when evaluating transportation processes unincorporated into the metals LCIs. We presume these results also apply to transport-dominated LCIs, such as those evaluating alternative uses for wastes. Within this context, consider for example the use of urban waste or waste biomass for energy production or the transfer of wastes between businesses pursuant to the principles of industrial ecology. In these systems, the life cycle flows of transport plus materials refining theoretically replace the life cycle of virgin or conventional feedstocks and should raise the importance of the contribution of transportation in the baseline system.

Next, we find that when incorporated into the metal LCIs, the contribution of commodity transport to the metals

Table 5 Transportation contribution to metals life cycles

	Primary aluminum	Secondary aluminum	Brass	Primary copper	Secondary copper	Cast iron ^a	BOF steel ^a	EAF steel ^a	BOF stainless ^a	EAF stainless ^a
Total life cycle energy consumption	0.3–0.5%	0.5–0.8%	0.7–0.9%	0.7–1.1%	0.6–0.9%	0.7–1.1%	2–2.9%	0.5–0.8%	0.3–0.5%	0.2–0.3%
Life cycle fossil fuel consumption	0.5–0.7%	0.6–0.9%	0.9–1.3%	1.1–1.6%	0.8–1.2%	1–1.5%	2.2–3.1%	0.7–1.1%	0.4–0.6%	0.3–0.4%
Life cycle petroleum consumption	1–1.4%	3.2–4%	2–2.6%	2.2–3%	1.5–2.1%	3.1–3.9%	4–4.8%	2.6–3.4%	1.9–2.6%	1.5–2.1%
Life cycle air emissions										
NM _{VOC}	10.8–15.4%	11.1–16.2%	2.8–3.8%	1.4–2%	3.2–4.8%	12.5–17.8%	18.9–25.9%	12.7–18.4%	6.7–9.8%	4.8–7.1%
CO	0.6–0.9%	10.6–15.6%	3.9–5.3%	2.4–3.6%	3–4.5%	0.6–0.9%	0.5–0.7%	2.7–4.1%	1–1.5%	2.9–4.3%
NO _x	15–20.3%	19.7–27.1%	7.8–9.9%	4.3–6.1%	7.6–10.9%	25.2–33%	43.1–52.4%	20.3–27.7%	12.3–17%	8.4–11.9%
PM ₁₀	0.4–0.6%	1–1.4%	0.2–0.3%	0.1–0.1%	0.2–0.3%	0.5–0.8%	0.6–0.9%	0.8–1.2%	0.2–0.3%	0.2–0.2%
SO _x	0.6–0.9%	1.4–2.2%	0.2–0.3%	0.1–0.1%	1.5–2.3%	2.1–3.2%	12.1–17.5%	1.4–2.3%	0.8–1.2%	0.5–0.8%
CH ₄	1.9–2.9%	2.4–3.7%	4.1–5.8%	4.5–6.8%	3.9–6.1%	4.1–6.3%	12.2–17.8%	2.9–4.6%	1.9–2.9%	1.2–1.9%
N ₂ O	10.6–12.9%	8–12.2%	18.9–21.3%	6.5–9.2%	8.2–12.2%	12.9–18.6%	47.2–57.7%	8.7–12.9%	6–8.9%	3.8–5.8%
CO ₂	2–3.1%	4.5–7.1%	4.8–6.7%	6.1–9%	4.1–6.4%	4.3–6.6%	8.2–12.3%	3.7–5.7%	2.2–3.4%	1.5–2.3%
Life cycle contribution to global warming (from CO ₂ , N ₂ O, and CH ₄) ^b	2–3.1%	4.5–7%	4.9–6.8%	6–9%	4.2–6.4%	4.4–6.7%	8.4–12.5%	3.7–5.7%	2.2–3.4%	1.5–2.3%

^a These results compare well with those presented by the American Iron and Steel Institute (2006) and AusLCANet (1998).^b Equivalency factors of 23, 296, and 1 CO₂-equivalents were used for CH₄, N₂O, and CO₂ respectively.

life cycle is important for select emissions, undetectable for energy, and displays little variation in the results related to distance confidence intervals and the inclusion of backhaul (seeing on average a 2% change in the contribution of commodity transport to the metal LCIs for variation in assumptions). Finally, our normalization revealed a very small, consistent commodity transport contribution of NO_x for all metals and a small contribution to all emissions by carbon steel on a national scale.

Thus for our sliding scale, we find travel distances, distance confidence intervals, and the inclusion of backhaul to be important to transportation processes and presumably transport-dominated LCIs; we find travel distances to be important when commodity transport is incorporated into metal LCIs; and we find commodity transport not important to our normalized results for the metals studied. Further contribution has been demonstrated by Spielmann and Scholz (2005), who found infrastructure processes accounting for as much as 50% of select transport unit process life cycle emissions, but we note that even this gross addition would not drastically change our normalized results. Still, because commodity transportation was found to be important in our un-normalized results, we note that, depending upon the goal of the study, intentional omission of commodity transport in metal LCIs, and until shown otherwise other LCIs, without further investigation may not be defensible.

We presume all LCIs will fall somewhere on this sliding scale, and that the estimation methods presented here will be useful in future studies. In the absence of specific hauling conditions, assumptions related to backhaul add consideration of empty vehicle/vessel movement which can double the distance of a single transport leg. Similarly, assumptions related to co-location can eliminate the distance of a single transport leg. For both backhaul and co-location, development of national and commodity-specific rules-of-thumb based on classes of commodities, transport phases (solid, liquid, gaseous), and regional hazardous materials transport laws could be easily incorporated into LCIs and may be appropriate for studies when specific origins and destinations are known. Interestingly, regional hazardous materials transport laws potentially dictate longer transport distances when no-passage-zones are considered. We also note a concern that if regional water quality degrades below that needed for industrial purposes, water transport (which would presumably include empty-truck backhaul) in these regions might be an important LCI consideration.

Whereas it may be possible to develop reliable regional and commodity-specific rules-of-thumb for backhaul and co-location that can be automated within the construction of a LCI, two aspects of comprehensive commodity transport remain. First, assuming regional commodity transportation could be characterized, a comprehensive regionally and

technology-specific production mix database is needed to complete the picture. For example, again, consider the production of US steel mill products with only 74% of steel mill products produced in the country (United States Geological Society 2003). The International Iron and Steel Institute provides regionally-specific production mix data (% use of BOFs, EAFs, and open-hearth furnaces) in the *Steel Statistical Yearbook* (International Iron and Steel Institute 2004a, b) which shows substantial regional variation throughout the globe with differences in transportation arising from the use of distributed vs. central plants (i.e., mini-mills). In fact, we note that increased reliance on mini-mills would reduce not only the contribution of commodity transport to US emissions related to the steel life cycle but also the contribution of steel use overall. In this way, our results favor locally produced steel, in the same way select LCA food and bioproducts practitioners have suggested advantages in locally produced feedstocks. However, a database combining such data for all commodities does not exist.

Second is the estimation of transport distances. Ideal data would capture specific hauling conditions, estimated on a point-to-point basis for the exact material being hauled. Here, instead of representing the exact material hauled, we assumed the movement of commodity groups (by SCTG code) to be representative of the hauling distance. This assumption worked well when used by He and Wang (2000) as they were evaluating fuels production which is primarily dominated by commodities that are represented by single SCTG codes, but is less compelling for commodities in general. The commodity group assumption becomes even less compelling when modeling for example specialty chemicals, dominantly used in for example electronics and advanced materials manufacturing. Further, we have used only single-mode share-weighted distances, leaving companies who report only multi-mode data out of our assessment.

Given these concerns, modeling only ocean, barge, rail, and highway transport from the national production sites to the point-of-use (i.e., we did not consider imports), we found transportation did selectively register among our LCIs as an important contributor to emissions but not energy consumption, with no apparent rules-of-thumb for commodity groups. We next note that we considered on average the transport of almost 50 commodities per metal aggregated into 21 commodity groups, and only for the US. If we had access to even commodity group studies for the countries importing metals to the US, we would only need to estimate ocean transport (with US data available from the FAF) to add imports to our transportation assessment. At an average of 50 commodities per metal, the question of diminishing returns presents itself. One way to determine this point is to model all imports, which seems at present impractical.

Another way to look at the diminishing returns of transportation data collection is to consider when commodity transportation can actually be changed. For example, local sources for energy, construction materials (including mini-mill steel), and food are possible and LCIs aimed at justifying local sourcing might ‘stop’ data collection when inventory flows exceed some target percentage for the study at hand (so that a maximum transport distance for a preferred system is recommended). A similar approach might be taken for facility siting or if a change in the fuel or powertrain type for a fleet is being investigated. If in these studies specific origins and destinations are known, we recommend assumptions related to backhaul be clearly stated and also be considered as for potential changes (i.e., less frequent travel of empty vehicles).

From a data management standpoint, the modeling parameters described here, by the SETAC Workgroup, and by Spielmann and Scholz can be divided into those that should be accounted for in transport unit process models and those that should be accounted for in unit process models using materials, with the latter accounting for transport from the point of production or sale. Location (e.g., where fuel is produced, where emissions occur, etc.), accidents, and noise may also play a role in data development. The results presented here and by Spielmann and Scholz indicate that the following can be important parameters in commodity transport modeling:

- *Parameters accounted for in transport unit process models* regional vehicle/vessel energy and emission intensities; load factor; vehicle/vessel manufacturing, maintenance, and disposal; and infrastructure construction, operation/ maintenance, and disposal.
- *Parameters accounted for in unit process models using transported materials* load; distance of transport for fronthaul; and distance of transport for backhaul.

This assumes regional vehicle/vessel energy and emission intensities are dictated by vehicle/vessel type and size; engine type; fuel type/constituents; exhaust gas cleaning; and local traffic conditions (e.g., some regions are characterized by heavier traffic conditions or more up-hill driving) as can be seen when comparing, for example, the energy intensity of road transport vehicles presented by Spielmann and Scholz (2005) ranging from 3.1–3.8MJ/tkm for 16-t lorries used in Switzerland or Europe and at 2.0MJ/tkm for US class 8 trucks as applied here). This grouping of parameters reflects our argument that to support the development of a representative contribution or dominance analysis (the quantification of the contribution of the life cycle of a unit process or set of unit processes to a particular impact), unit processes using commodities should be owed the burdens of the transport (as opposed to those burdens being borne by the production or sale of the commodity).

Finally, when included in a LCI, the contribution of transportation as part of LCA results, the contribution should include transportation fuel production energy use and emissions. Essentially, transport data models that are developed from detailed parametric models (which should also be named in meta data) and should be presented as a *class* of vehicles/vessels, with each class capturing variations in these meta data. Such transport model classes are for example critical to the construction of LCIs that are location-specific (noting, e.g., that traffic conditions vary substantially from region-to-region) and LCIs that are temporally-specific (noting, e.g., fuel constituent requirements are being changed subject to national laws which will change emissions over time). Next, unit processes using transported materials should demand these specific transport models and include meta data noting the load, distance of transport for fronthaul and backhaul, and potentially losses due to accidents as appropriate to the study.

As more attention is being paid to the contribution of transportation contribution within system life cycles such as food and bioproducts systems, we note that well-documented assessments culminating in transparent results can be used to identify local sourcing or facility location priorities for metals and thus for materials beyond notorious transportation-oriented systems. Recommendations for future research start with assessments beyond than metals but also include the development of regional production mix databases and regional and commodity-specific rules-of-thumb for backhaul and co-location. For the metal case studies, future research will include: (1) assessment of a broader range of emissions, land use, and noise, (2) inclusion of equipment and infrastructure construction, maintenance and disposal, accidents, waste management processes, and air cargo (3) inclusion of transportation from and to overseas destinations, and (5) further investigation of the use of non-US process data to represent US operations.

References

- American Council for an Energy-Efficient Economy (1997) Asilomar Conference on Sustainable Transportation Energy Strategies, Decicco JM, Delucchi MA (eds) Transportation, energy, and environment: how far can technology take us? American Council for an Energy Efficient Econom, Washington, DC 278p
- American Iron and Steel Institute (2006) Steel glossary. American Iron and Steel Institute, Washington, DC
- AusLCANet (1998) Australian LCA Network: tinplate report and SimaPro 5.0—Australian LCI data on steel, auslcanet.rmit.edu.au/
- Baumel C, Hurburgh C, Lee T (1985) Estimates of total fuel consumption in transporting grain from Iowa to major grain-importing countries by alternative modes and routes. Iowa State University, Ames
- Braam J, Tanner T, Askham C, Hendriks N, Maurice B, Malkki H, Vold M, Wessman H, de Beaufort A (2001) SETAC-Europe LCA working group 'Data availability and data quality' energy, transport and waste models. Int J Life Cycle Assess 6(3):135–139
- Bureau of Transportation Statistics (2004) Transportation–commodity flow survey United States, EC02TCF-US. U.S. Census Bureau, Washington, DC
- Ekvall T, Frees N, Nielsen P, Person L, Ryberg A, Weidema B, Wesnaes M, Widheden J (1998) Life cycle assessment on packaging systems for beer and soft drinks. Main report. Danish Environmental Protection Agency (Environmental Project 399), Copenhagen
- Emissions Factors and Policy Applications Center (1986) AP42 5th Edition compilation of air pollutant emission factors, vol. 1: stationary point and area sources: iron and steel production. U.S. Environmental Protection Agency, Washington, DC
- Energy Information Administration (2006) Annual energy review, www.eia.doe.gov/emeu/aer/contents.html
- Eriksson I, Elmquist H, Stern S, Nybrant T (2005) Environmental systems analysis of pig production—the impact of feed choice. Int J Life Cycle Assess 10(2):143–154
- Federal Highway Administration (2002) Freight analysis framework highway capacity—Version 1: methodology report. Department of Transportation, Washington, DC
- Fowler J (2001) The commodity flow survey and hazardous materials safety data: perspectives on use, content, and needs for the future. Transportation Research Board 80th Annual Meeting, Washington, DC
- Frees N, Weidema B (1998) Life cycle assessment of packaging systems for beer and soft drinks: energy and transport scenarios. Danish Environmental Protection Agency (Environmental Project 406), Copenhagen
- He D, Wang M (2000) Contribution of feedstock and fuel transportation to total fuel-cycle energy use and emissions. Society of Automotive Engineers. SAE 2000-01-2976
- International Energy Agency (2006) Statistics and balances, www.iea.org/Textbase/stats/
- International Iron and Steel Institute (2004a) Steel statistical yearbook. Brussels, Belgium
- International Iron and Steel Institute (2004b) Worldwide LCI database for steel industry products methodology report, www.worldsteel.org
- Jørgensen A, Ywema P, Frees N, Exner S, Bracke R (1996) Transportation in LCA: a comparative evaluation of the importance of transport in four LCAs. Int J Life Cycle Assess 1(4):218–220
- Jungmeier G, Werner F, Jarnehammar A, Hohenthal C, Richter K (2002) Allocation in LCA of wood-based products: experiences of cost action E9—part II. Int J Life Cycle Assess 7(6):369–375
- Office of Transportation and Air Quality (2000) Analysis of commercial marine vessels emissions and fuel consumption data, EPA420-R-00-002. U.S. Environmental Protection Agency, Washington, DC
- Office of Air and Radiation (2006) Airtrends. U.S. Environmental Protection Agency, Washington, DC
- Ramjeawon T (2004) LCA of cane-sugar on the island of Mauritius. Int J Life Cycle Assess 9(4):254–260
- Silvenius F, Grönroos J (2003) Fish farming and the environment results of inventory analysis. Finnish Environment Institute, Helsinki
- Spielmann M, Scholz R (2005) Life cycle inventories of transport services—background data for freight transport. Int J Life Cycle Assess 10(1):85–94
- Swiss Centre for Life Cycle Inventories (2006) ECOINVENT—the Swiss national life cycle inventory database, www.ecoinvent.ch/

- United States Geological Society (2003) Minerals yearbook. U.S. Department of the Interior, Washington, DC
- United States Geological Society (2005) Mineral commodity summaries. U.S. Department of the Interior, Washington, DC
- Upper Great Plains Transportation Institute, North Dakota State University: Fargo, www.ugpti.org/pubs/pdf/SP143.pdf
- Vachal K, Reichert H (2000) Identity preserved grain—logistical overview. Upper Great Plains Transportation Institute Identity Preserved Grain
- Wang M (2005) The greenhouse gases, regulated emissions, and energy use in transportation (GREET) Model: Version 1.6. Argonne National Laboratory: Argonne (unit process data extracted prior to final software results), www.transportation.anl.gov/software/GREET/
- Woods L (2006) Modeling the transport of raw materials in life cycle assessment. Thesis in partial fulfillment of the requirements for the degree of Master of Science. University of Washington, Seattle